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Our goal is to develop the technological foundation of advanced haptic systems and to assemble that technology into a useful surgical simulator. The surgical simulator we envision will allow training of biomedical procedures in a virtual environment that features realistic interaction with simulated anatomy and surgical tools through haptic force feedback, 3D graphics, and sound. In addition to direct training, surgical emulators could be used to assess surgical performance and play a role in certification. This report describes our progress in building such a system.

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February 2, 1998

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Look and Feel:

Haptic Interaction for Biomedicine

1997 Final Report

Introduction

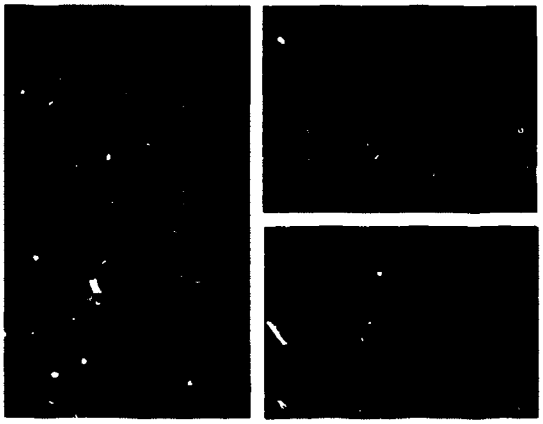

Figure 1: Photograph of trainee using BDI Surgical Simulator. Computer graphics creates 3D views of the virtual organs which are presented stereoscopically. Real surgical tools are attached to force feedback devices to measure the trainee's motions and feed back forces to the hands. Physics-based simulations mediate interactions between tools and organs.

People use their hands to touch, manipulate, and learn about the world around them. Interaction through touch and manipulation is known as haptic interaction. We are working to develop advanced haptic technology that allows human users to touch, feel, grasp, and manipulate a set of special objects: objects located remotely, objects too small, too large, or too dangerous for normal human interaction, or virtual objects that exist only in simulated worlds.

Advanced haptic interaction will have a wide range of applications in biomedical, military, and civilian areas. It will allow design engineers to "pick up" new designs, "try them out," and see how they behave, before they ever leave the drawing board. Engineers will sculpt the shapes of new parts in the computer, as though made of clay. Remote experts will aid the local novice in performing delicate procedures. Medical students will train by manipulating virtual organs, without risk to human patients or animals. Students will probe any part of the virtual patient with impunity and view a wide range of conditions from any vantage point. This work will enable applications ranging from familiarization and training in domains requiring hand/eye skills (surgery, mechanics, maintenance, for example) to the enhancement of operations in remote, scaled, unfamiliar, and hazardous environments.

Our goal is to develop the technological foundation of advanced haptic systems and to assemble that technology into a useful surgical simulator. The surgical simulator we envision will allow training of biomedical procedures in a virtual environment that features realistic interaction with simulated anatomy and surgical tools through haptic force feedback, 3D graphics, and sound. In addition to direct training, surgical emulators could be used to assess surgical performance and play a role in certification. This report describes our progress in building such a system.

In the first year of this effort we focused on developing the basic technology and methods needed to build interactive haptic applications. In the second year of effort, we have assembled these components into several prototype systems. We have built integrated systems for surgical anastomosis, heart palpation and aircraft maintenance. These systems were built upon a common software foundation that includes modules for virtual haptic interaction, physics-based simulation, and computer graphics. In the last year of effort, we extended the simulator to accommodate measurement of surgical performance. We used the simulator in a preliminary test comparing the performance of medical students and experienced vascular surgeons.

Integrated Haptics Applications

Our advanced haptic systems consist of a mechanical force-feedback device, a real-time computing system, a dynamic simulation system, and computer graphics and sound (Figure 2). Next we describe these systems: a simulator for surgical anastomosis, a version of the anastomosis simulator that includes performance assessment software, demonstration of virtual heart palpation that uses volumetric 3D visual displays, and a simulator for aircraft maintenance. While the functionality of each of these systems is significantly different, they all build upon a common foundation and thus contribute to the overall goal of developing advanced haptic systems.

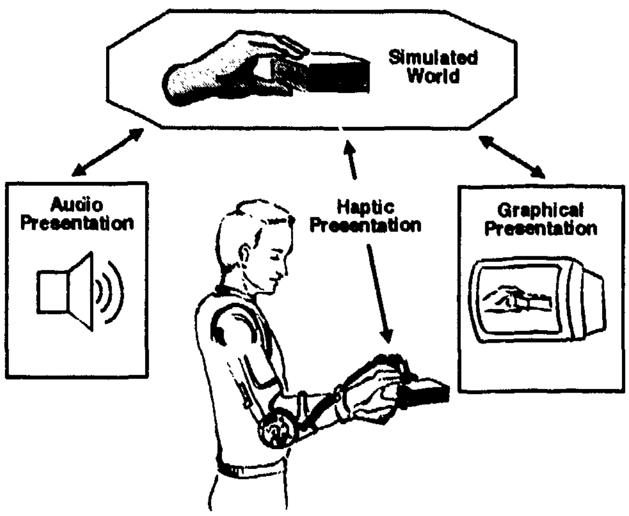

Figure 2: Haptic, Graphic, and Audio Presentation of a Virtual Object

The Virtual Surgery Simulator

The primary focus of activity of the ``Look and Feel" project remains the development of the Virtual Surgery Simulator (Figure 1). This simulator is an integrated system that allows users to reach into a virtual human body to touch, feel, grasp and suture two deformable tubes. The user holds real surgical tools connected to Phantom force feedback devices. By holding a needle holder in one hand and forceps in the other, the user can manipulate two virtual tube organs and suture them together to practice an end-to-end anastomosis. The forces of interaction between the tools and the simulated tubes are reflected to the user with the Phantom while the virtual workspace is visually displayed using 3Dcomputer graphic images. Coordinated visual and tactile displays allow the user to work in an intuitive way while exploring the basic techniques of the surgical anastomosis.

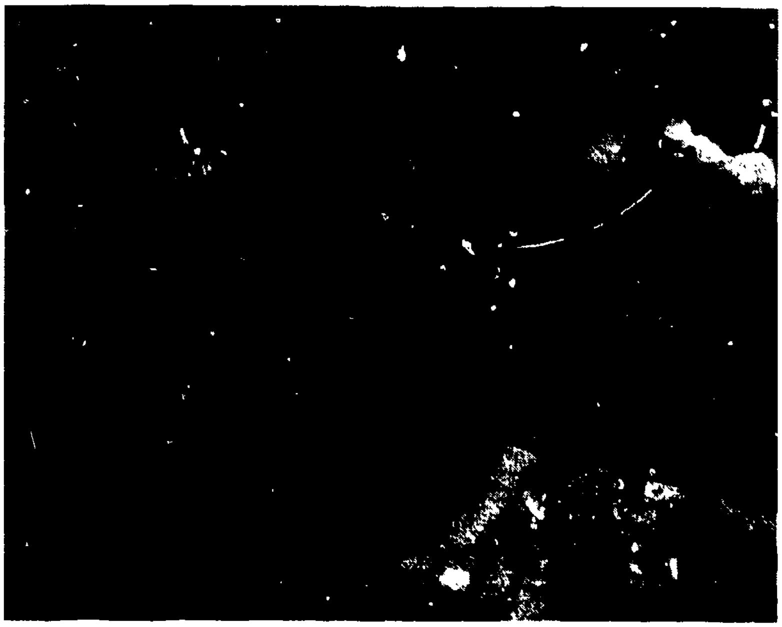

Figure 3: *The Virtual Surgery Simulator features deformable tubes that can be sewn together using needle, suture, needle holder, and forceps.*

The simulated elements in the anastomosis demonstration are two deformable tubes, forceps, needle holder, needle and suture. The look and feel of the tubes can be changed to represent different anatomical elements. Tube diameter, thickness, length, compliance, surface friction, and resistance to puncture are just a few parameters that can be used to accommodate different surgical applications. Texture mapped graphics derived from photographs of real biological tissue help make the simulated elements look realistic.

We have constructed a Virtual Surgery Station that allows the surgeon and surgical subject to be in the correct relative position (Figure 4). The user stands with hands at table height holding the forceps and the needle holder. Looking down at his hands, the surgeon instead sees a mirror reflecting the computer graphic image of the subject and the virtual tools. This image is produced in approximately the correct location by using an SGI monitor mounted overhead. A hand rest allows the surgeon to stabilize his hands for delicate manipulation. We have delivered a version of this Virtual Surgery Station to Dr. Tom Krummel at Pennsylvania State's Hershey Medical Center. Dr. Krummel intends to integrate this trainer into his virtual training lab at the Hershey Medical Center. We have also demonstrated this system at the meeting of the Association of Academic Health Centers, the society for Vascular Surgeons Conference and the American College of Surgeons Conference .

***Figure 4**: The virtual reality surgical trainer lets you see, tou , and feel simulated organs using 3D computer graphics and advanced force feedback technology. Using a needle holder and forceps attached to force feedback devices, the user can grasp, poke, pluck, and suture flexible tube organs. The user can feel the vessels when touched and the vessels move realistically in response to touch. The surgical station uses a mirror arrangement to place the 3D image of the patient in the correct position relative to the user. This system allows the user to control a virtual needle and thread to perform a simulated end-to-end anastomosis.*

Performance Assessment with the VR Surgical Trainer

The virtual reality (VR) surgical trainer is a modification of the simulator described above that assesses skill level during a simulated surgical procedure. The virtual surgical performance is evaluated based upon measures of damage to the tissue, needle technique, and other dynamic parameters. An initial experiment has compared the performance of surgeons and medical students on a simulated surgical task. We found that on average the surgeons performed better than the medical students.

Virtual reality simulations hold the potential to improve surgical training in a manner analogous to its impact on the training of pilots. The advantages of VR for surgical training include a reduction in operating room time required for training, the quantification of trainees' performances, and an ability to provide experiences independent of a hospital's limited patient population. An interactive virtual reality surgical trainer could improve the training of surgeons and also play a role in the accreditation process.

We conducted an experiment to compare the performance of medical students and vascular surgeons using the VR surgical trainer. Both groups were given the task of repeatedly inserting a curved needle through a simulated vessel. Twelve Harvard Medical School students and nine vascular surgeons from five Boston area hospitals participated in the study. We tracked eight parameters during the study: 1) tissue damage, 2) accuracy, 3) peak force applied to the tissue, 4) time to complete the task, 5) surface damage to the tissue, 6) total tool movement. 7) average angular error from an ideal needle path, and 8) an overall error score. The users were given visual feedback regarding their performance after each trial of the experiment.

The surgeons tended to outperform the medical students by having less tissue damage (See for example Figure 4). The surgeons' average performance scores were better than those of the medical students for all of the measured parameters (See Figure 5). These differences were statistically significant ($p<0.05$) for: damage to the tissue, time to complete the task, excessive tool motions, proper angle of the needle, and overall error score.

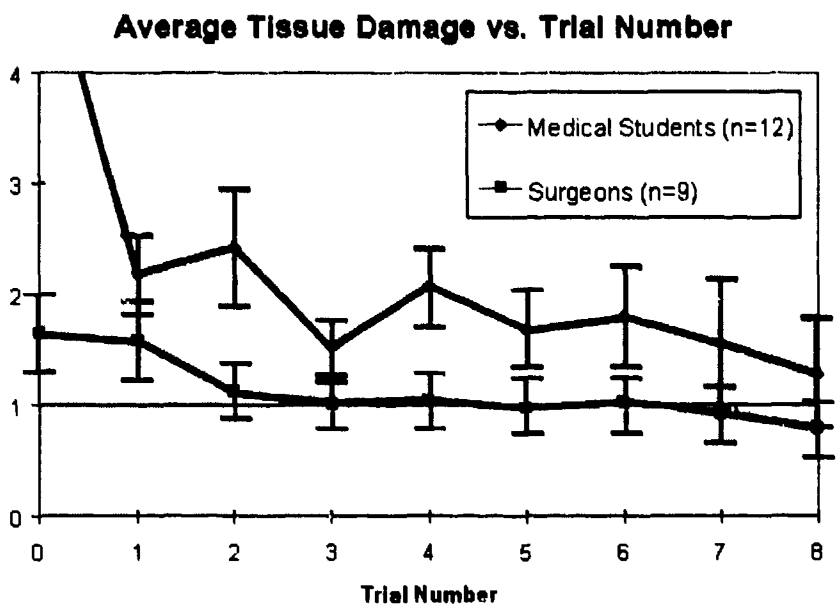

Figure 5: The average tissue damage values are plotted versus the trial number in the experiment. Tissue damage is defined as the sum of forces that exceed a tissue damage threshold.

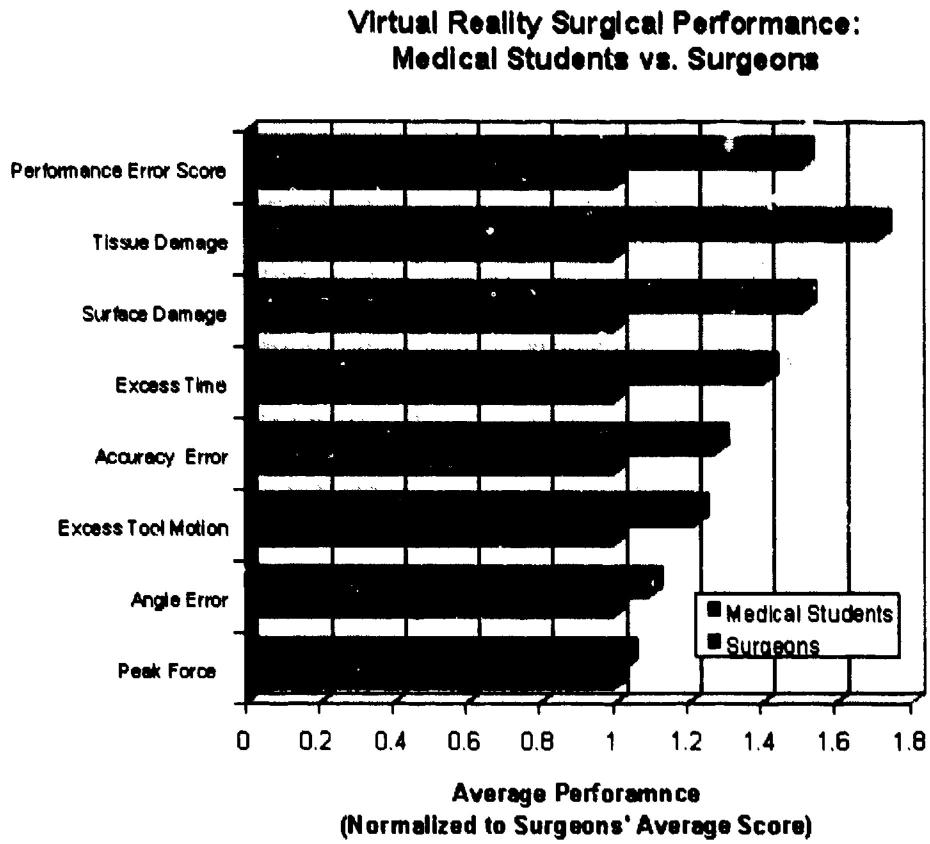

***Figure 6**: The bar chart displays the average medical student and surgeon performances for the simulated surgical task. The values have been normalized to the average surgeon values. The surgeon values were better than the medical student values for all eight of the metrics. Five of the differences (performance error score, tissue damage, excess time, excess tool motion, and angle error) were statistically significant ($p<0.05$).*

We have developed a VR trainer that tests a user's technique in placing a needle through a simulated vessel. An initial experiment has compared the simulated surgical performance of medical students and vascular surgeons. On average, the surgeons outperformed the medical students in the 8 parameters that were measured (statistically significant for 5 of the parameters). These results suggest that the VR surgical trainer may be useful in quantifying surgical skill.

Palpation of a Beating Heart

Boston Dynamics Inc. in conjunction with Digital Media Associates has created a system that allows the user to touch, poke and pluck a simulated, beating heart with medical instruments (Figure 6). The user can touch a 3D volumetric display of the heart with medical instruments mounted to Phantom force-feedback devices. The user actually feels the heart whenever the physical tool "touches" the floating 3D image because the visual and haptic images of the heart are coincident in space. An audible heart beat is synchronized with the visual and haptic heart displays.

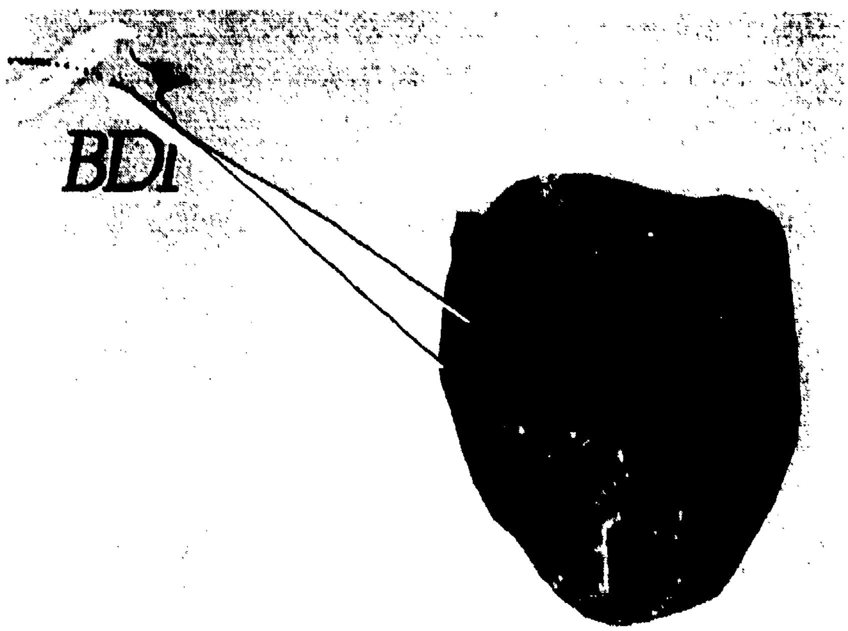

***Figure 7**: The Virtual Heart: the user can see, feel, and hear the heart beat as well as poke and pluck its deformable surface*

The volumetric 3D display is created by projecting computer graphic images of a beating heart onto a screen contoured to the shape of a heart. The image of this screen is projected into the haptic workspace using mirrors. The projection system, the 3D-RT, was built by Digital Media Associates. It consists of a high quality projector, the heart contoured screen, and the mirroring system. BDI created the haptic algorithms, dynamic simulation, computer graphics, and sound of the beating, deformable heart. This unique combined display system makes it easier to touch virtual objects by putting haptic and visual images together.

Virtual Aircraft Maintenance Training

The technology that provides the foundation for advanced haptics systems is largely independent of the application area. In a separately funded project we developed the Virtual Aircraft Maintenance Trainer (Figure 8). This project has leveraged the funding for surgical simulator development because the basic issues regarding dynamic simulation, haptic force-feedback, and computer graphics are common to all haptics systems. We developed the Virtual Aircraft Maintenance Trainer to explore the feasibility of replacing expensive mock-ups of aircraft used for maintenance training with less expensive computer hardware and software. The virtual maintenance trainer we built allows a user to perform the essential elements of two real-world maintenance training tasks performed by the US Marines on theAV8B aircraft, a vertical take-off and landing attack fighter. One task is diagnosis of a failed Radar Warning Receiver System Built-In-Test (RWR BIT).The second maintenance task is adjustment of the Vernier/Non-Linear Nosewheel Steering Linkage.

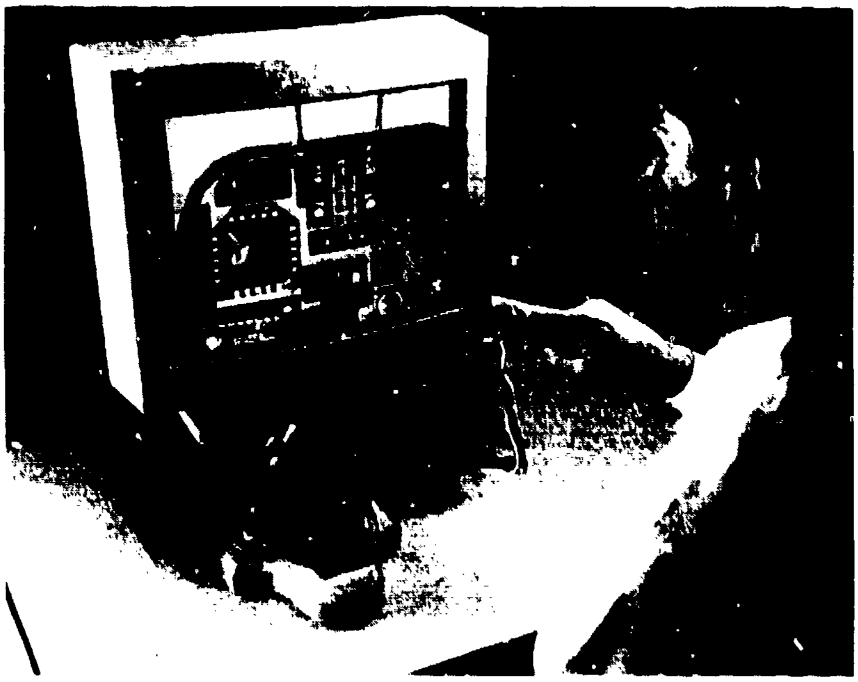

Figure 8: The Virtual Maintenance Trainer allows the user to push buttons, throw toggle switches, turn dials, observe lights, and listen to audible tones, and manipulate linkages during the evaluation and adjustment of aircraft systems

Using the Virtual Maintenance Trainer the trainee can push buttons, throw toggle switches, and turn dials in the cockpit, as well as observe indicator lights, listen for audible tones and measure voltages as part of running and diagnosing an avionics self-test. Simulations of the cockpit panels, buttons, dials, switches, and electrical pins allow the technician to see, feel, and hear the avionics system operations. The linkage adjustment procedure involves manipulating a simulated four-bar linkage through its range of motion, measuring the forces required to move the linkage between two hard stops, and adjusting those forces by tightening or loosening a friction nut on the linkage. The dynamic simulation of the linkage obeys the kinematic and dynamic constraints of the real physical device and allows interactive attachment or detachment from the rudder pedal actuator, and joint friction adjustment. The user can feel the shapes of the links in the mechanism, as well as the forces needed to move it.

Progress on Components of an Advanced Haptic System

An integrated system for advanced haptic interaction needs to have three parts: a part that mechanically interfaces to the user's hand (and/or arm), a part that mediates the interaction between the hand and virtual or remotely located objects, and a part that simulates how the objects will behave when touched. These components are force feedback devices, haptic algorithms, and physics-based simulation, respectively. In Table 1 we summarize our progression a list of development tasks for advanced haptic systems including the virtual surgical simulator. Next we detail our progress in these areas.

Table 1: Progress List for Advanced Haptic System Development

Advanced Haptic Interface Devices: The haptic device is the mechanical interface that allows the user to touch and manipulate a virtual or remotely located object.

- Phantom haptic device interfaced to SGI and PC
- Instrumented medical tool attachments
    - Debakey forceps
    - needle holder
- Virtual medical tools
    - debakey forceps
    - needle, needle holder, and suture
    - scalpel with scalpel holder
    - hemostatic forceps
    - intestinal forceps
    - dissecting forceps
    - scissors
    - retractor
- Instrumented gimbal measures tool position and orientation
- Powered, two finger attachment designed and tested (MIT Task)

Haptic Algorithms: These algorithms mediate the forces the user feels with the Haptic Interface Device.

- Two handed interaction demonstrated
- Two finger manipulation demonstrated
- Rigid body contact force models
- Flexible body contact force models
- Coulomb friction
- Haptic textures for bumps, sand paper, ridges
- Haptic textures mapped onto shapes
- Contact detection between 3D polygonal shapes
- Contact detection between point or line and flexible tubes
- Contact detection between point and grid maps

Physics-Based Simulation: Real-time physics-based simulation is used to calculate the behavior of objects, interactions among objects, and interactions between objects and the user.

- Automatic simulation generation for rigid body systems
- Loadable object shapes from CAD files
- Programmable bulk properties of simulated objects
- Compliant flexible skin
- Compliant flexible tube
- Calcified artery
- Compliant beating heart
- Coordinated 3D volumetric display and haptic display
- Suture two tubes together with surgical needle and suture
- Texture mapped graphics

Advanced Haptic Interface Devices

The Phantom haptic device is a light weight, high bandwidth mechanical interface that allows the user to touch and manipulate a virtual or remotely located object. Haptic fidelity and high resolution are important for conveying a detailed sense of touch and are thus emphasized over kinematic complexity and high force capacity. High fidelity and resolution are obtained by maximizing bandwidth through the design of stiff, lightweight, and low friction structures and transmissions.

The Phantom is interfaced to both a PC and an SGI graphics workstation. Haptic algorithms and object simulation code are run on the PC while the graphics workstation is used for 3D visual display. The Phantom is both an input device and an output device. It can apply forces back to the user along the three translational axes. The position and orientation of the tool or probe mounted to its tip are measured using encoders. Instrumented surgical tools or mechanical tools mounted to the Phantom provide a familiar interface to the user. A powered, two finger device has been designed by the MIT group and tested at BDI. This device can apply a gripping torque to the user to simulate the sensation of grasping an object with two fingers. Further development of the haptic device is underway and will include piezo-vibration stimulators for ultra-high bandwidth sensation, multi-fingertip interaction, and large workspace.

Haptic Algorithms

Haptic algorithms mediate the exchange of forces between simulated objects and the user. The two most important haptic algorithms are for contact detection and contact force modeling. Contact detection is used for determining when two simulated objects are touching. Contact force models are used to compute the forces of interaction between simulated objects. Contact forces can arise from interpenetration of objects, sliding between objects, or from haptic textures applied to surface geometry.

Contact Detection

The contact detection algorithm determines when simulated objects collide or when the user is touching a simulated object. The algorithms use the geometry of the simulated objects to compute the distance separating them. We use several contact detection algorithms that are optimized for real-time performance and that are tuned to the object model type. For example, we use a linear-time Lin and Canny type algorithm for contact between convex rigid polyhedra. This general contact algorithm is insensitive to the number of polygons on an object. We use a grid-depth type algorithm for point contact on polyhedra with mild concavities and a specialized algorithm for computing contact between points or lines and a flexible tube.

Contact Force Models

The interaction force between two touching simulated objects is computed with a contact force model. We use penalty method techniques in our contact force models. Characteristics such as surface compliance, friction, textures, puncturability, and surface feature resolution are controlled by the contact force model and can be modified to suit the application.

Haptic Texture Mapping

The goal of haptic texture mapping is to permit haptically perceivable textures to be overlaid on basic object geometry. A haptic texture is a force model whose parameters depend upon the spatial location of the haptic device relative to the underlying geometry. Our basic technique is to superpose forces due to haptic textures and forces due to contact with the underlying geometry. The spatial information for a haptic texture is derived from loadable images and can be used to change different parameters in the contact force models. Using haptic textures we have created the feeling of scratchy sand paper, smooth bumps, and discrete ridges on a flat surface. We are currently working on mapping haptic textures to rigid objects and deformable organ models.

Physics-Based Simulation

Our system uses real-time physics-based simulation to calculate the behavior of objects, interactions among objects, and interactions between objects and the user. Objects can be isolated bodies, mechanical linkages, or more complicated things like tool mechanisms, deformable tissues, or organs. A basic idea of the work is that physics-based simulation allows virtual objects to move as real objects do; obeying the laws of physics, they feel like real objects when touched, and move realistically in response to touching.

The foundation of our object simulator is software that we developed in previous work that automatically creates highly-optimized dynamic simulations of things that move from simple descriptions of the objects. The physical simulations include material properties than can be changed by the user to tune the feel of the object. For example, we can change the mass of a rigid body, the compliance of its surface, or the coefficient of friction between a surface and the haptic device.

Rigid Object Loader

A general object loader is working that allows multiple 3D objects to be loaded, dynamically simulated, and touched or manipulated. The software includes automatic contact detection, equation generation, and 3D graphics. The shape of these objects can be defined with a CAD file that describes their surface geometry. The geometry is used for both visualization and contact detection. Bulk properties of the bodies like mass, coefficient of friction, or surface impedance can be specified by the user. The haptic tool used for manipulation in the virtual environment is a special kind of simulated object. It's position and orientation are driven by the Phantom. The forces of interaction between it and other simulated objects are computed from the haptic algorithms.

Flexible Tissue

To support the simulation of surgical procedures, we have expanded our simulation library to include prototype simulations of flexible tissue and flexible tubes. At BDI we are using flexible tissue simulation techniques that strive for computational simplicity and speed while providing convincing behavior. One prototype flexible tissue simulation included a planar surface that deformed when pushed or pulled. Rigid objects with varying surface compliance could be positioned beneath the flexible tissue to simulate a palpation task. We also have simulations of whole and severed hollow tubes. The tubes move when touched and the surfaces deform when the tubes are poked or plucked. By varying the radii of the tubes with time we can simulate the look and feel of a pulsing vessel. The flexibility or surface deformation of a flexible tube can be tuned to best approximate the feel of biological material.

Commercialization and Related Work

BDI is developing and selling products that are closely related to the ARPA funded work.

- BDI is marketing Tangible Reality(TM), a turn-key virtual environment system that includes visual images, sound, and touch. The system consists of a force-feedback device, a real-time simulation computer, a physics-based simulation environment, simulated objects, real-time 3Dcomputer graphics, real-time 3D sound effects, and networking. Early versions of the product will support standard sets of physics-based simulated objects. Later versions will support user-defined objects and deformable objects. This product provides an initial channel for commercialization of results from the proposed research. For example ``palpating in" and ``haptic texture mapping" are obvious candidates for enhancing the product as we understand and develop them.

- In a joint project with Musculographics Inc., we have delivered the beta version of a limb trauma simulator to the US Army at Fort Bragg. BDI was responsible for the haptic components on this project. Three additional simulators will be delivered this year.

- We won a competitive bid to develop a knee anthroscopy simulator for the American Board of Orthropedic Surgeons. We will demonstrate this simulator to the Board in February. They are enthusiastic about possible commercial applications of the simulator for testing and accreditation.

- Demonstrated the surgical simulator along with the performance assessment software at the Society of Vascular Surgeons conference in January 1997 and the American College Surgeons conference in October 1997.

- We delivered a special version of Tangible Reality designed for training surgical procedures. This version of the system supports two-handed anastomosis. Thomas M. Krummel, M.D., Chair of the Department of Surgery at Penn State's Hershey Medical Center is building ``The Virtual Hospital." The VR Anastomosis Simulator is a key feature in his concept for reducing the cost and improving the quality of medical teaching.

- We delivered to Digital Media Associates a system that allows the user to touch, poke and pluck a simulated, beating heart with medical instruments. The user can touch a 3D volumetric display of the heart with medical instruments mounted to Phantom force-feedback devices. The user actually feels the heart whenever the physical tool ``touches" the floating 3D image because the visual and haptic images of the heart are coincident in space. An audible heart beat is synchronized with the visual and haptic heart displays. We have plans to continue this joint project to combine force feedback haptics, dynamic simulation, and 3D volumetric displays.

- Nissho Electronics Corp. is a Japanese distributor of the BDI Tangible Reality System.

- In an effort to demonstrate the applicability of VR technology to aircraft maintenance training we developed the VR Maintenance Trainer for the Joint Advanced Strike Technology Program. This project significantly leveraged our ARPA-funded project and offers other military applications.

Conclusions

As part of the ``Look and Feel" project we have assembled much of the basic technology required to build integrated haptics systems that allow the user to see, hear, and touch simulated objects. These worlds can include rigid body, multi-link, dynamic objects, deformable organs, and articulated tools that can be manipulated by the user. Haptic algorithms detect collisions between simulated objects and compute contact forces between them. Force-feedback devices convey the forces of interaction to the user. Physics-based simulation computes the response of simulated objects to external forces and 3D computer graphics display the visual scene to the user. Using these component technologies we have constructed prototypical advanced haptic systems that allow the user to perform procedures such as surgical anastomosis, heart palpation, and aircraft maintenance. While these prototype demonstrations do not replicate all the detail found in real surgeries or training environments, we believe they take a significant step towards the goal of building useful virtual training environments. In the future, we will work towards commercialization of this technology.

APPENDDIX A

Computer Assisted Orthopaedic Surgery First Annual North American Program (CAOS/USA 97)

A NOVEL VIRTUAL REALITY SURGICAL TRAINER WITH FORCE FEEDBACK: SURGEON VS. MEDICAL STUDENT PERFORMANCE

O'Toole, R.[1,2], Playter, R.[1], Blank, W.[1], Cornelius, N.[1], Roberts, W.[1], and Raibert, M.[1]

1. Boston Dynamics Inc., Cambridge, MA, USA.
2. Harvard Medical School, Harvard-MIT Division of Health Sciences and Technology, Boston, MA, USA.

INTRODUCTION: We have developed an interactive virtual reality (VR) surgical trainer with force-feedback to simulate the anastomosis of vessels (See Figure 1). The VR surgical trainer assesses skill level during a simulated surgical procedure. The virtual surgical performance is evaluated based upon measures of damage to the tissue, needle technique, and other dynamic parameters. An initial experiment has compared the performance of surgeons and medical students on a simulated surgical task. We found that on average the surgeons performed better than the medical students.

Figure 1. The virtual reality surgical trainer lets you see, touch, and feel simulated organs using 3D computer graphics and advanced force feedback technology. Using a needle holder and forceps attached to force feedback devices, the user can grasp, poke, pluck, and suture flexible tube organs. The user can feel the vessels when touched and the vessels move realistically in response to touch. The surgical station uses a mirror arrangement to place the 3D image of the patient in the correct position relative to the user. This system allows the user to control a virtual needle and thread to perform a simulated end-to-end anastomosis.

CLINICAL RELEVANCE: Virtual reality simulations hold the potential to improve surgical training in a manner analogous to its impact on the training of pilots. The advantages of VR for surgical training include a reduction in operating room time required for training, the quantification of trainees' performances, and an ability to provide experiences independent of a hospital's limited patient population. An interactive virtual reality surgical trainer could improve the training of surgeons and also play a role in the accreditation process.

METHODS: We conducted an experiment to compare the performance of medical students and vascular surgeons using the VR surgical trainer. Both groups were given the task of repeatedly inserting a curved needle through a simulated vessel. Twelve Harvard Medical School students and nine vascular surgeons from five Boston area hospitals participated in the study. We tracked eight parameters during the study: 1) tissue damage, 2) accuracy, 3) peak force applied to the tissue, 4) time to complete the task, 5) surface damage to the tissue, 6) total tool movement, 7) average angular error from an ideal needle path, and 8) an overall error score. The users were given visual feedback regarding their performance after each trial of the experiment.

RESULTS: The surgeons tended to outperform the medical students by having less tissue damage (See for example Figure 2). The surgeons' average performance scores were better than those of the medical students for all of the measured parameters (See Figure 3). These differences were statistically significant ($p<0.05$) for: damage to the tissue, time to complete the task, excessive tool motions, proper angle of the needle, and overall error score.

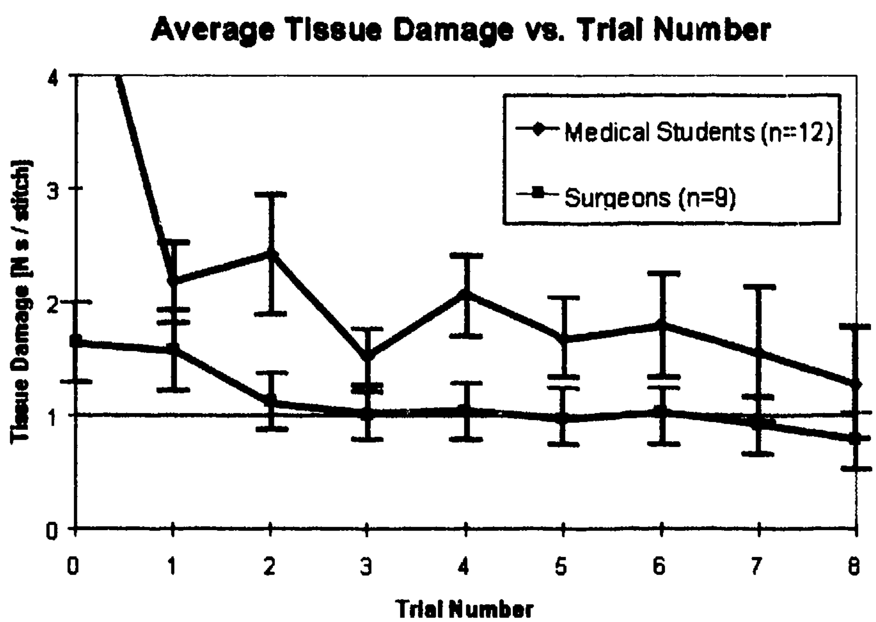

Figure 2. The average tissue damage values are plotted versus the trial number in the experiment. Tissue damage is defined as the sum of forces that exceed a tissue damage threshold.

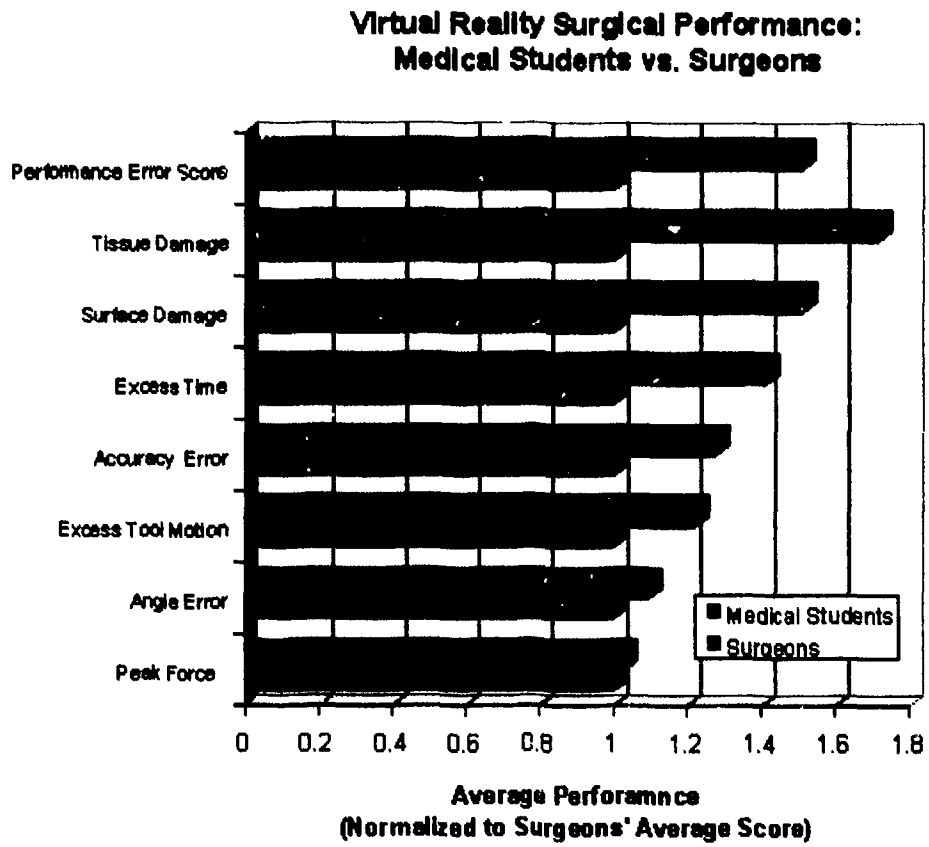

Figure 3. The bar chart displays the average medical student and surgeon performances for the simulated surgical task. The values have been normalized to the average surgeon values. The surgeon values were better than the medical student values for all eight of the metrics. Five of the differences (performance error score, tissue damage, excess time, excess tool motion, and angle error) were statistically significant ($p<0.05$).

CONCLUSIONS: We have developed a VR trainer that tests a user's technique in placing a needle through a simulated vessel. An initial experiment has compared the simulated surgical performance of medical students and vascular surgeons. On average, the surgeons outperformed the medical students in the 8 parameters that were measured (statistically significant for 5 of the parameters) . These results suggest that the VR surgical trainer may be useful in quantifying surgical skill.

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A virtual surgery simulator using advanced haptic feedback

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Summary. Simulators based on virtual reality offer great promise for training future surgeons. We are developing a surgical simulator with emphasis on providing the user with a sense of touch in addition to the senses of sight and sound. Users hold real medical instruments and touch, grasp, and suture two simulated tube organs as they practice end-to-end anastomosis procedures. The medical instruments are attached to force feedback devices that convey the forces of interaction to the user. The behaviour of the tubes is derived from a physics-based simulation. Computer graphics provide real-time texture-mapped images of the surgical scene. The system is currently operational and its training value will be evaluated using medical students and experienced surgeons.

Keywords: surgical simulation, haptic feedback, force feedback, virtual reality

Introduction

Someday surgical simulators based on virtual reality will allow surgical training without the use of human patients, hospital space or animals. Surgical simulators will train sensory-motor skills, perceptual tasks and cognitive decision-making, all in the context of performing relevant surgical procedures. In addition to allowing medical students to practice routine procedures, surgical simulators will allow students to encounter patients with rare medical conditions or unexpected complications and practice techniques to handle these situations. Using today's opportunistic methods, only very experienced surgeons are exposed to the wide range of conditions and complications that can occur. In addition to direct training, surgical simulators could be used to assess surgical performance and play a role in certification.

Computer-based surgical simulation has been under development for several years [1]. The first simulator to use virtual medical instruments [2] allowed the user to visually tour an abdomen populated with simplified organs. More recent work in neurosurgery [3, 4] and endoscopy [5], focused on increasing visual realism by using data from real patients. Other groups have increased the level of interactivity with the virtual model by using passive input devices to 'grab' and move anatomical parts [6, 7].

The use of physics-based models has improved the realism and predictive capability of surgical simulators for pre-operative planning [8, 9]. By using real surgical tools as input devices, minimally invasive surgical simulators approximate actual surgeries when interacting with the virtual model [10]. Force feedback is being used in a laparoscopic surgery trainer [11, 12] and lumbar punctures [13, 14].

Our focus in surgical simulation is to give the user a sense of touch, in addition to the senses of sight and sound. Users are able to reach into the virtual environment with their hands to touch, feel and manipulate simulated organs, in addition to seeing and hearing them. Interaction through touch and manipulation is known as *haptic* interaction. Haptic interaction plays a prominent role in the surgical trainer we are building.

Virtual anastomosis

The surgical simulator we are building focuses on open surgery anastomosis, the task of suturing tube-like organs together. Anastomosis is ubiquitous in surgery, applying to blood vessels, oesophagus, ureters, bronchi, colon, ducts and other organ systems found throughout the human body. The Virtual Surgery Simulator (Figures 1 and 2) allows the user to practice the elements of an

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Figure 1. The Virtual Surgery Simulator uses a mirror to overlay visual imagery from the virtual work space onto the surgeon's hands.

end-to-end anastomosis including touching, grasping and suturing two compliant tube organs with forceps, needle and needle driver. By combining visual, audio and haptic displays, this trainer allows the user to work on simulated organs in an intuitive way while using familiar medical instruments.

The hardware (Figure 3) used in the surgical simulator includes two Phantom force feedback devices (manufactured by SensAble Technologies, Cambridge, MA) that provide high fidelity force feedback, a high-end PC that simulates virtual objects and computes haptic algorithms, and a Silicon Graphics Maximum High Impact Indigo 2 workstation that provides 3-D graphics and sound.

The user works through a set of real surgical tools that have been connected to force feedback devices. Holding a needle holder in one hand and a forceps in the other, the user can grasp and stabilize a tube while puncturing it with a needle held in the jaws of the needle holder. The user sutures the tubes together by puncturing each tube in sequence, then pulling the suture material tight. The forces of interaction between the tools and the simulated tubes are calculated by a simulation computer, then conveyed to the user through the force feedback devices. Visual images of the interaction are displayed through a 3-D graphics computer. Coordinated visual and tactile displays allow the user to work in an intuitive way while exploring the basic techniques of the surgical anastomosis.

The Surgery Simulator has subsystems for real-time 3-D computer graphics, physics-based simulation and haptic

Figure 2. The Virtual Surgery Simulator: view from the surgeon's perspective.

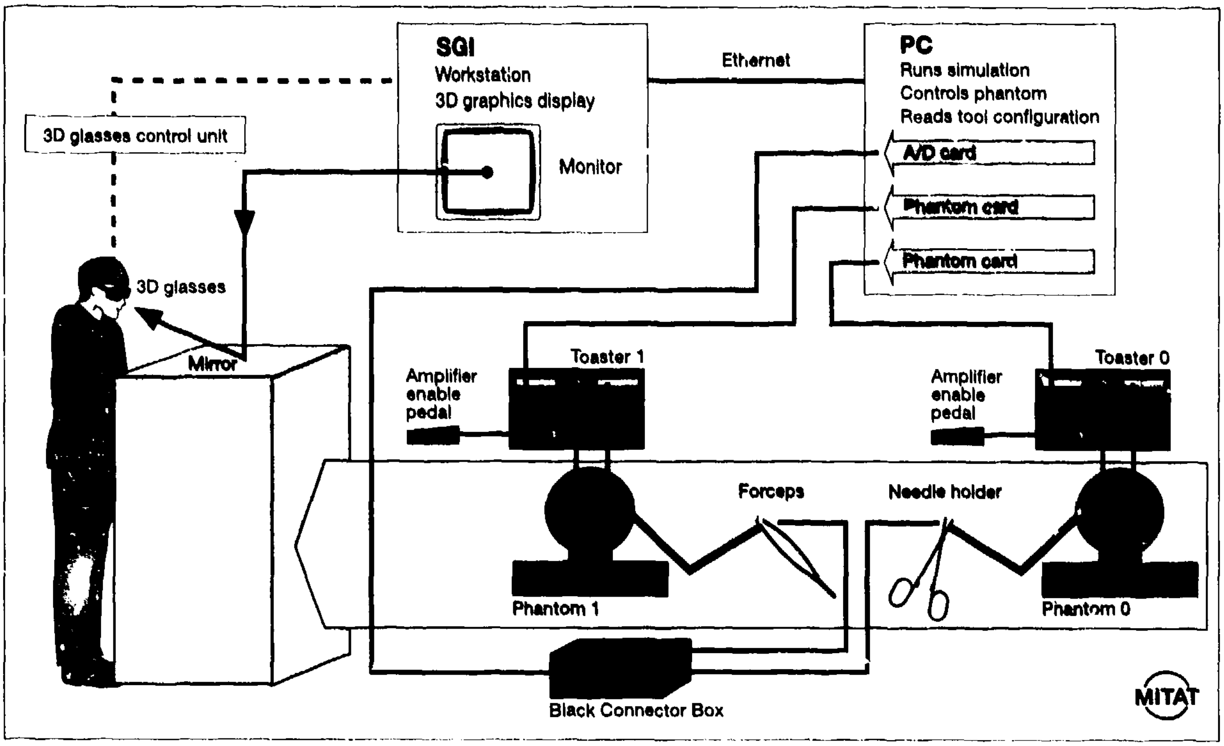

Figure 3. Hardware configuration for the surgical simulator.

interaction. The quality of the interaction depends on how realistically the haptic computer simulates the virtual objects, how well the haptic algorithms compute contact forces, how well the force feedback device conveys those forces back to the user, and how well the haptic feedback synchronizes the visual and auditory feedback to the user. The immersive quality of the simulator depends on both the speed of the displays and the realism of interaction.

The computer graphics are provided by a conventional system: it generates stereo, texture-mapped images using custom OpenGL software running at 20 Hz on a Silicon Graphics Maximum Impact. The visual display of the simulator includes two tubes, a background and models of the surgical tools (needle, suture, needle holder and forceps). The polygon count of the entire scene with two tubes is about 1200 polygons. Images are displayed through a mirror system that places the visual workspace in front of the user at about waist level. This arrangement allows the visual workspace and haptic workspaces to overlap, resulting in a natural working configuration (Figures 1 and 2). A hand rest allows the surgeon to stabilize his or her hands for delicate manipulations.

The software for the system includes several components:

- Deformable tube simulation,
- Fast contact detection,
- Contact force calculation,
- Kinematics for force feedback devices,
- Force feedback device drivers,
- 3-D graphics and sound on SGI computers.

Physics-based simulation is used to model the deformable tubes in the system and compute their response to interactions with the surgical tools. We designed a specialized tube simulator that has good real-time performance at the expense of generality. The tube simulator uses a lumped mass model for motions of the free end, an elastic spine for tube bending and stretching, and local surface deformation models that permit puckering where the tube is pinched, and dimpling where it is poked. Physical parameters of the tubes such as the diameter, thickness, length, compliance, mass, surface friction and resistance to puncture can be modified to represent different anatomical elements. Rather than measure the elasticity of biological skin, we asked practicing surgeons to evaluate the feel of the simulated tissue in our surgical station. We adjusted parameters of the tissue model until the physicians felt it was realistic. The simplified tube simulation does not yet support layers of tissue, tissue folding or contact against puckered or dimpled regions of the tube.

Haptic algorithms mediate the exchange of forces between simulated objects and the user. The two most important haptic algorithms are those that detect when objects contact one another, and that compute the forces created when contact occurs. We use several contact detection algorithms that are optimized for real-time performance and that are tuned to the object model type. For example, we use a linear-time Lin and Canny [15] type algorithm for contact between convex rigid polyhedra. For point contact on static polyhedra with mild concavities we store the polyhedra in memory as a series of 'depth' values, then compare the depth of the tool point to that of the polyhedra. To calculate contact forces between objects, we use penalty method techniques that calculate contact force from spring and damper models and the interpenetration of the two objects. Characteristics such as surface compliance, friction, texture, puncturability and surface feature resolution are controlled by the contact force model and can be modified to suit the application.

The haptic display rate required for a good quality sense of touch depends upon the objects being simulated. Convincing interactions with rigid objects generally require 1000 Hz while interactions with more compliant objects, like soft tissue, are less demanding. The surgery simulator has an update rate for the haptic algorithms and simulation of about 400 Hz. To achieve this rate we limited the number of possible contacts between different objects in the scene. For example, the tools cannot contact one another and the needle can only contact the tube at its tip until puncture. After puncture, the contact point travels along the needle shaft so that the tissue 'holds' the needle at the proper point.

Discussion

The goal of this work is to build a surgical simulator that can be used for training surgical procedures and evaluating surgical performance. It is unlikely that all the detail found in real surgeries will be captured by surgical simulators in the near term. However, it is feasible to capture enough of the real experience to provide useful training of surgical procedures and performance evaluation. Despite its many limitations, we believe the surgical simulator takes a significant step towards this realistic goal.

Our current work involves expanding the capabilities and improving the performance of the surgical simulator. We are adding performance measurement and display features to the simulator. These recording, display and playback features will help the surgical trainee review and improve surgical technique by providing quantitative measures of needle placement accuracy, force level and tissue damage. Once these features are working, the user will be able to practice important elements of surgical anastomosis, including proper handling of the medical tools, techniques for grasping tubes and suturing techniques including proper needle orientation, needle placement, puncture forces, suture spacing and suture tightening.

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